CDS 101: Lecture 1.1
Introduction to Feedback and Control

Richard M. Murray
27 September 2004

Goals:

- Give an overview of CDS 101/110; describe course structure, administration
- Define feedback systems and learn how to recognize main features
- Describe what control systems do and the primary principles of control

Reading (available on course web page):

- Åström and Murray, *Analysis and Design of Feedback Systems,* Ch 1

Course Administration

CALIFORNIA INSTITUTE OF TECHNOLOGY
Control and Dynamical Systems

CDS 101 - Analysis and Design of Feedback Systems
CDS 110 - Introduction to Control Theory
Fall 2004

Instructor
R. Murray, 109 Steele
murray@cds.caltech.edu
Office hours: Fri, 3-4 pm or by appt

Teaching Assistants
Steve Waydo (head TA: waydo@cds.caltech.edu),
Domitilla Del Vecchio, Asa Hopkins, Haomiao Huang,
Hao Jiang, Mortada Mehyar, Kevin Tang

Co-instructors
Anand Asthagiri (ChE)
Tim Colonius (ME)
Ali Hajimiri (EE)
Steven Low (CS/EE)
Hideo Mabuchi (Ph/CS)
Steven Low (CS/EE)

Lectures
CDS 101: M2-3, F2-3; 74 Jorgensen
CDS 110: M2-3, W2-3; 74 Jorgensen

TA office hours: Sun, 5-6 pm, 110 Steele

Recitations (CDS 110 only): Schedule to be announced

Course Overview CDS 101/110 provides an introduction to feedback and control in physical, biological, engineering, and information sciences. Basic principles of feedback and its use as a tool for altering the dynamics of systems and managing uncertainty. Key themes throughout the course will include input/output response, modeling and model reduction, linear versus nonlinear models, and local versus global behavior.

CDS 101 is a 6 unit (2-0-4) class intended for advanced students in science and engineering who are interested in the principles and tools of feedback control, but not the analytical techniques for design and synthesis of control systems. CDS 110 is a 9 unit class (3-0-6) that provides a traditional first course in control for engineers and applied scientists. It assumes a stronger mathematical background, including working knowledge of linear algebra and ODEs. Familiarity with complex variables (Laplace transforms, residue theory) is helpful but not required.

Class homepage Information on the class is available via the class homepage: `http://www.cds.caltech.edu/~murray/cds101`. All course handouts and other administrative data about the course are available via the class homepage.

Lectures, recitation sections and office hours The main course lectures are on MWF from 2-3 pm in 74 Jorgensen. CDS 101 students are not required to attend the Wednesday lectures, although they are welcome to do so. The Friday lectures are optional for CDS 110 students and will provide supplemental material on applications of control.

In addition to the main lectures, a series of problem solving (recitaiton) sessions are run by the course teaching assistants. These recitation sessions are broken up according to areas. All CDS 110 students are required to attend at least one problem solving session per week. The recitation session schedule will be determined in the first week of classes and will be posted on the course web page.

Grading The final grade will be based on homework sets, a midterm exam, and a final exam:

- Homework: 50%
  Homework sets will be handed out weekly and due on Mondays by 5 pm to the box outside of 109 Steele. Late homework will not be accepted without prior permission from the instructor.
- Midterm exam: 20%
  A midterm exam will be handed out at the beginning of midterms week (27 Oct) and due at the end

Course syllabus

- CDS 101 vs CDS 110ab
- Lectures
- Grading
- Homework policy
- Course text and references
- Office hours
- Class homepage
- Software
- Course outline

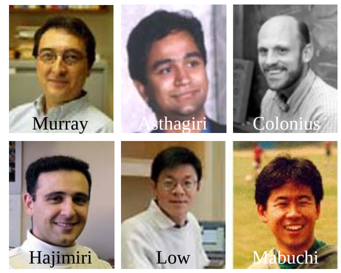
- Lecture DVDs: 102 Steele, Box G
- Course load: keep track of hours

CDS 101/110 Instructional Staff

Lecturer: Richard Murray (CDS)

Co-Instructors

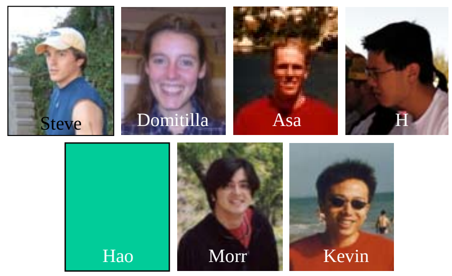
- Anand Asthagiri (ChE)
- Tim Colonius (ME)
- Ali Hajimiri (EE)
- Steven Low (CS/EE)
- Hideo Mabuchi (Ph/CDS)



Head TA: Steve Waydo (ME)

TAs

- Domitilla Del Vecchio
- Asa Hopkins
- Haomiao "H" Huang
- Hao Jiang
- Morr Mehyar/Kevin Tang



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Mud Cards

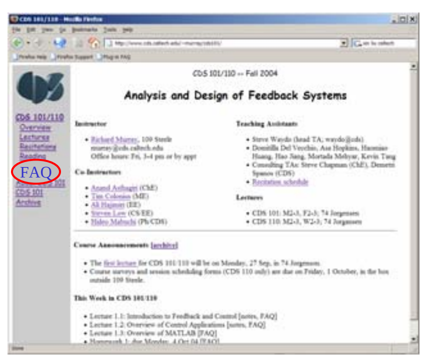
Mud cards

- 3 x 5 cards passed out at beginning of each lecture
- Describe "muddiest" part of the lecture (or other questions)
- Turn in cards at end of class
- Responses posted on FAQ list by **8 pm** on the day of the lecture (make sure to look!)

> What does closed loop mean? You used this term without defining it.

Class FAQ list

- Searchable database of responses to mud cards and other frequently asked questions in the class



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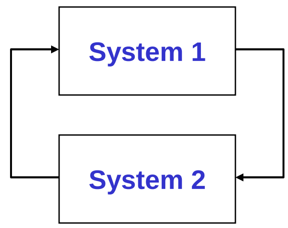
What is Feedback?

Miriam Webster:

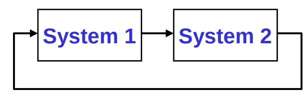
the return to the input of a part of the output of a machine, system, or process (as for producing changes in an electronic circuit that improve performance or in an automatic control device that provide self-corrective action) [1920]



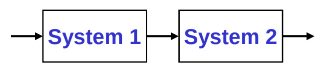
Feedback = mutual interconnection of two (or more) systems

- System 1 affects system 2
- System 2 affects system 1
- Cause and effect is tricky; systems are mutually dependent

Terminology



Closed Loop



Open Loop

Feedback is ubiquitous in natural and engineered systems

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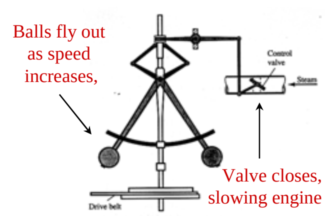
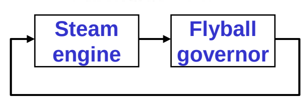
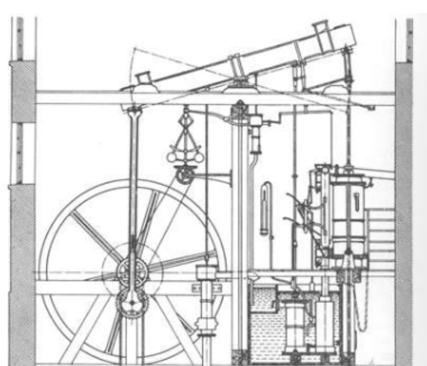
Example #1: Flyball Governor

"Flyball" Governor (1788)

- Regulate speed of steam engine
- Reduce effects of variations in load (disturbance rejection)
- Major advance of industrial revolution







Boulton-Watt steam engine

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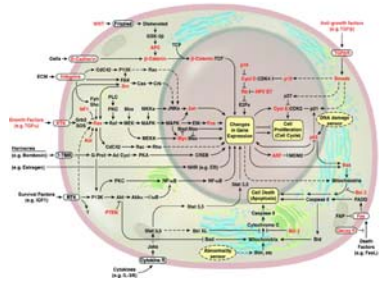
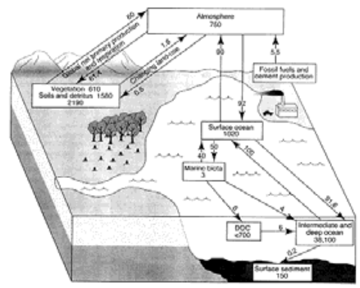
Other Examples of Feedback

Biological Systems
- Physiological regulation (homeostasis)
- Bio-molecular regulatory networks

Environmental Systems
- Microbial ecosystems
- Global carbon cycle

Financial Systems
- Markets and exchanges
- Supply and service chains





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Control = Sensing + Computation + Actuation

In Feedback "Loop"

Actuate
Gas Pedal

Sense
Vehicle Speed

Compute
Control "Law"

Goals
- Stability: system maintains desired operating point (hold steady speed)
- Performance: system responds rapidly to changes (accelerate to 65 mph)
- Robustness: system tolerates perturbations in dynamics (mass, drag, etc)

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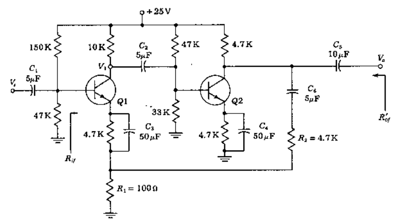
Two Main Principles of Control

Robustness to Uncertainty through Feedback

- Feedback allows high performance in the presence of uncertainty
- Example: repeatable performance of amplifiers with 5X component variation
- Key idea: accurate *sensing* to compare actual to desired, correction through *computation* and *actuation*



Design of Dynamics through Feedback

- Feedback allows the dynamics of a system to be modified
- Example: stability augmentation for highly agile, unstable aircraft
- Key idea: interconnection gives *closed loop* that modifies natural behavior

X-29 experimental aircraft

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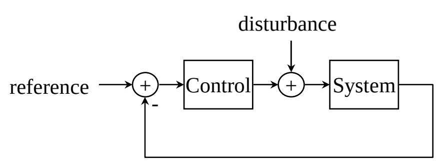
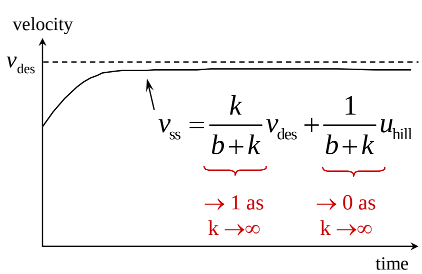
Example #2: Cruise Control



$$m\dot{v} = -bv + u_{\text{engine}} + u_{\text{hill}}$$
$$u_{\text{engine}} = k(v_{\text{des}} - v)$$



Stability/performance

- Steady state velocity approaches desired velocity as k → ∞
- Smooth response; no overshoot or oscillations

Disturbance rejection

- Effect of disturbances (hills) approaches zero as k → ∞

Robustness

- Results don't depend on the specific values of *b, m,* or *k* for *k* sufficiently large

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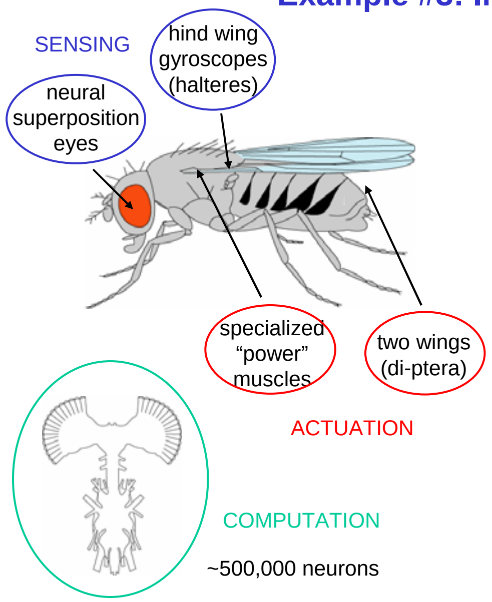
Example #3: Insect Flight



More information:

- M. D. Dickinson, Solving the mystery of insect flight, *Scientific American,* June 2001
- CDS 101 seminar : Friday, 10 Oct 03

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Control Tools

Modeling

- Input/output representations for subsystems + interconnection rules
- System identification theory and algorithms
- Theory and algorithms for reduced order modeling + model reduction

Analysis

- Stability of feedback systems, including robustness "margins"
- Performance of input/output systems (disturbance rejection, robustness)

Synthesis

- Constructive tools for design of feedback systems
- Constructive tools for signal processing and estimation (Kalman filters)

MATLAB Toolboxes

- SIMULINK
- Control System
- Neural Network
- Data Acquisition
- Optimization
- Fuzzy Logic
- Robust Control
- Instrument Control
- Signal Processing
- LMI Control
- Statistics
- Model Predictive Control
- System Identification
- µ-Analysis and Synthesis

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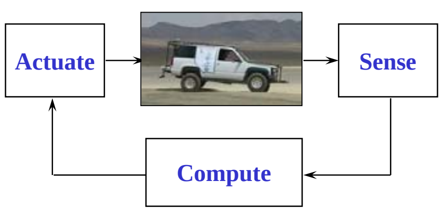
Overview of the Course

Wk	Mon/Wed	Fri
1	Introduction to Feedback and Control	MATLAB tutorial, Steve W.
2	System Modeling	Linear algebra/ODE review, Steve W.
3	Stability and Performance	Control of cavity oscillations, T. Colonius
4	Linear Systems	Internet Congestion Control, S. Low
5	Controllability and Observability *Midterm exam*	Review for midterm, Steve W.
6	Transfer Functions	Piloted flight, D. McRuer (tentative)
7	Loop Analysis of Feedback Systems	Stability in Electronic Circuits, A. Hajimiri
8	Frequency Domain Design	Molecular Feedback Mechanisms, A. Asthagiri
9	Limits on Performance	Thanksgiving holiday
10	Uncertainty Analysis and Robustness *Final exam*	Review for final, TBD

Summary: Introduction to Feedback and Control



Control =

Sensing + Computation + Actuation

Feedback Principles

- Robustness to Uncertainty
- Design of Dynamics

Many examples of feedback and control in natural & engineered systems: